

# Numerical Modelling of Regenerative Liquid Propellant Guns with Annular Piston

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## ABSTRACT

The development of regenerative liquid propellant guns (RLPGs) needs due consideration of numerous interdependent parameters that affect its performance. To help in this task, computer simulation was undertaken to predict internal ballistics of a conceptual liquid propellant gun. The expected pressure and other important parameters are documented which serve as an aid to the hardware design of the regenerative liquid propellant guns.

## NOMENCLATURE

|            |   |
|------------|---|
| $\epsilon$ | Energy lost as a fraction of the total energy of subscript term |
| $\nu$      | Ratio of specific heats (gamma)                                 |
| $\tau$     | Time delay between liquid propellant injection and combustion   |
| $\rho(t)$  | Density at time $t$   |
| $\beta(t)$ | Bulk modulus at time $t$  |
| $A(t)$     | Area of cross-section   |
| $C$        | Discharge coefficient of liquid through annular vents           |
| $F(t)$     | Total force at time $t$   |
| $H_1$      | Heat lost in the barrel as fraction of total propellant energy  |
| $I$        | Impetus   |
| $K(t)$     | Kinetic energy of propellant gases at time $t$                  |
| $m$        | Mass  |
| $M_i(t)$   | Mass injected in time $t$                                       |
| $M_l(t)$   | Mass lost due to leakage in time $t$                            |
| $M_r(t)$   | Mass of igniter/propellant reacted in time $t$                  |

|             |   |
|-------------|---|
| $P(t)$      | Pressure at time $t$                        |
| $r(t)$      | Rate of combustion of igniter at time $t$   |
| $T(t), T_f$ | Temperature at time $t$ , Flame temperature |
| $U(t)$      | Volume at time $t$                          |
| $V(t)$      | Velocity at time $t$                        |
| $x(t)$      | Displacement at time $t$                    |
| $A$ & $B$   | Input parameter for bulk modulus            |

## Subscripts

|              |  |
|--------------|--|
| $ar, ad$     | Air in reservoir, air in damper chamber                          |
| $atm$        | Atmosphere   |
| $c, d, r$    | Combustion chamber, damper, reservoir                            |
| $df$         | Damper fluid   |
| $effd, effr$ | Effective air + fluid in damper, effective air + lp in reservoir |
| $gc$         | Gases in combustion chamber                                      |
| $lp, ip$     | Liquid propellant, igniter propellant                            |
| $lr, ld$     | Leakage vents in reservoir, leakage vents in damper              |
| $pi$         | Piston   |
| $pj$         | Projectile   |
| $rd$         | Control rod  |
| $vr, vd$     | Vents in reservoir, vents in damper                              |

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## 1. INTRODUCTION

Regenerative liquid propellant guns (RLPGs) with inline piston have been modelled<sup>1,2</sup>. These guns have several problems and there was a need to implement a new concept incorporating an annular piston and a movable control rod. A schematic of this concept is shown in Fig. 1. The igniter is used to initially pressurise the chamber which causes the control rod to move rearward. The liquid propellant (lp) flows from the reservoir to the chamber through the annulus between the control rod and the annular piston. The annular piston also moves rearward and the annular gap between it and the control rod decides the mass flow rate. The area of the annular piston facing the projectile side is larger than the one facing the liquid propellant side. This differential piston concept ensures that the annular piston keeps moving rearward even when the reservoir pressure is high.

## 2. MODEL

The model assumes that the initial pressure in the combustion chamber is generated by an igniter burning at a fixed rate. The injection process is controlled by the movement of the annular piston

and the control rod. The equations of pressure and temperature in the combustion chamber<sup>3</sup> are given by

$$P_c(t) = \frac{(1-H_1) [Mr_{lp}(t) I_{lp} + Mr_{ip}(t) I_{ip}]}{U_c(t)} - \frac{0.5(V_{gc}-1) [(1+\epsilon_{pj})m_{pj}V_{pj}(t)^2 + (1+\epsilon_{pi})m_{pi}V_{pi}(t)^2]}{U_c(t)} - \frac{0.5(v_{gc}-1) [(1+\epsilon_{rd})m_{rd}V_{rd}(t)^2 + K_{gc}]}{U_c(t)} \quad (1)$$

$$T_c(t) = \left[ \frac{(1-H_1)(Mr_{lp}(t) I_{lp} + Mr_{ip}(t) I_{ip})}{(v_{gc}-1)} - K_{gc} - (1+\epsilon_{pj})m_{pj}V_{pj}(t)^2 - (1+\epsilon_{pi})m_{pi}V_{pi}(t)^2 - (1+\epsilon_{rd})m_{rd}V_{rd}(t)^2 \right] \left[ \frac{Mr_{lp}(t) I_{lp}}{(v_{gc}-1)Tf_{gc}} + \frac{Mr_{ip}(t) I_{ip}}{(v_{gc}-1)Tf_{ip}} \right] \quad (2)$$

These equations are differentiated to obtain the required differential equations. The heat lost to the gun is assumed to be a fraction  $H_1$  of the propellant energy. The heat lost during the gun operations due to friction in projectile, annular piston and control rod is assumed to be a fraction of the kinetic energy of the respective part. This fraction is represented

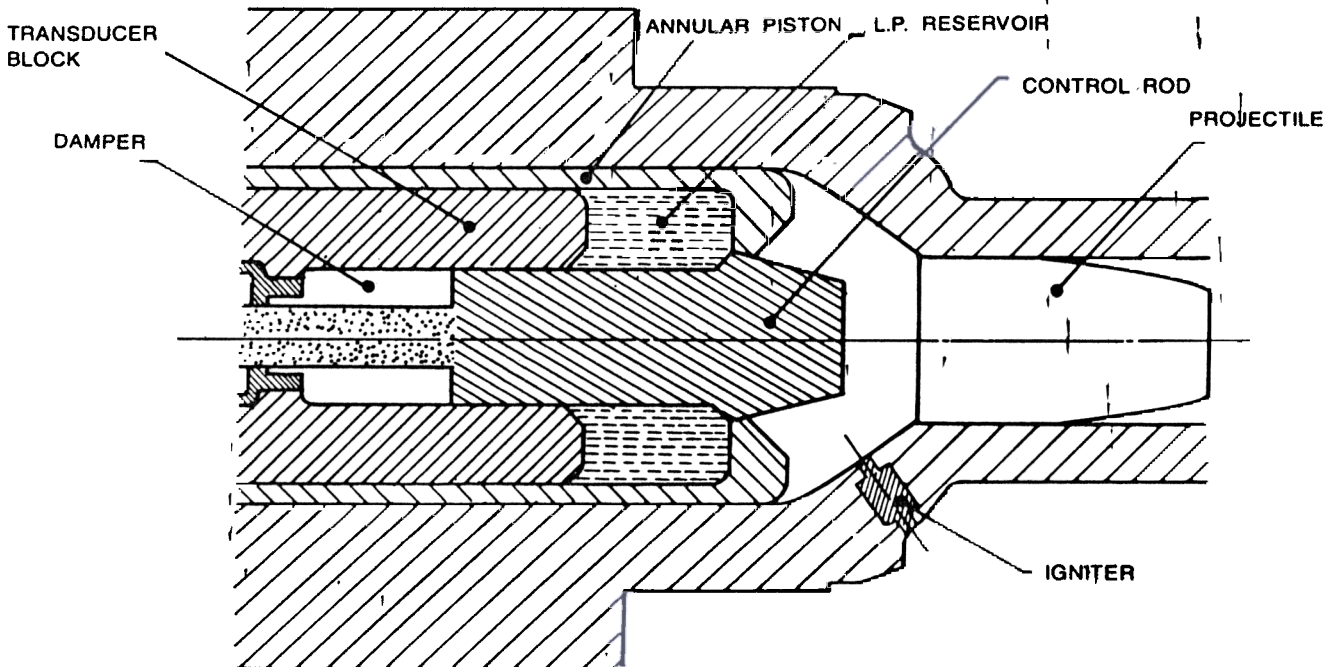


Figure 1. RLPG with annular piston and variable control rod

by  $\epsilon_{pj}$ ,  $\epsilon_{pi}$ ,  $\epsilon_{rd}$  for the projectile, annular piston and control rod energy, respectively<sup>4</sup>. It is assumed that the entire mass of  $lp$  entering the combustion chamber reacts instantaneously or after the user input delay. The amount of  $lp$  reacted is given by

$$M_{r_{lp}}(t) = M_{i_{lp}}(t - \tau) \quad (3)$$

The bulk modulus of the  $lp$  in reservoir and damper fluid ( $df$ ) in damper chamber changes drastically with pressure and is given by<sup>2,4</sup>

$$\beta_{effr} = A + B P_r(t) \quad (4)$$

$$\beta_{effd} = A + B P_d(t) \quad (5)$$

$A$  and  $B$  are user input parameters which need to be estimated experimentally. As experimental data were not available, the reported data were used<sup>2,4</sup>

In the case of ullage, the situation is more complicated because of the greater compressibility of air. The effective bulk modulus of  $lp$  in the reservoir and damper chamber is given by

$$\frac{1}{\beta_{effr}(t)} = \frac{U_{ar}(t)}{U_{ar}(t) + U_{lp}(t)} \frac{1}{\beta_{ar}(t)} + \frac{U_{ar}(t)}{U_{ar}(t) + U_{lp}(t)} \frac{1}{\beta_{lp}(t)} \quad (6)$$

$$\frac{1}{\beta_{effd}(t)} = \frac{U_{ad}(t)}{U_{ad}(t) + U_{df}(t)} \frac{1}{\beta_{ad}(t)} + \frac{U_{ad}(t)}{U_{ad}(t) + U_{df}(t)} \frac{1}{\beta_{df}(t)} \quad (7)$$

The bulk modulus of the  $lp$  and  $df$  is given by Eqns (4) and (5) respectively and that of air is given by the product of its  $v$  and its pressure. As the pressure in the reservoir and damper increases, the air gets compressed. The compression is assumed to be adiabatic and follows the equation

$$P_{ar} U_{ar}^{v_{ar}} = \text{constant} \quad (8)$$

$$P_{ad} U_{ad}^{v_{ad}} = \text{constant} \quad (9)$$

The  $lp$  and  $df$  are considered as compressible and the change in their respective densities is given by

$$\frac{d\rho_{lp}(t)}{dt} = \frac{\rho_{lp}(t) A_r V_{pi}(t)}{U_r(t)} - \frac{dM_{i_{lp}}/dt}{U_r(t)} - \frac{dM_{l_{lp}}(t)}{U_r(t)} \quad (10)$$

$$\frac{d\rho_{df}(t)}{dt} = \frac{\rho_{df}(t) A_r V_{pi}(t)}{U_d(t)} - \frac{dM_{i_{df}}/dt}{U_d(t)} - \frac{dM_{l_{df}}(t)}{U_d(t)} \quad (11)$$

The pressures in the reservoir and damper are given by

$$\frac{dP_r(t)}{dt} = \frac{\beta_{effr}(t) (A_r V_{pi}(t) - C_{vr} A_{vr}(t) V_{vr}(t) - C_{lr} A_{lr}(t) V_{lr}(t))}{U_d(t)}$$

$$\frac{dP_d(t)}{dt} = \frac{\beta_{effd}(t) (A_r V_{rd}(t) - C_{vd} A_{vd}(t) V_{vd}(t) - C_{ld} A_{ld}(t) V_{ld}(t))}{U_d(t)}$$

The pressure in the combustion chamber and the pressure in the  $lp$  reservoir generates forces which act on either side of the annular piston. The equations of motion of the piston are given by

$$\frac{dV_{pi}(t)}{dt} = \frac{P_c(t) (A_{pi} - A_{vr}(t)) - P_r(t) (A_r - A_{vr}(t))}{m_{pi}} \quad (14)$$

$$\frac{dx_{pi}(t)}{dt} = V_{pi}(t) \quad (15)$$

The pressure in the combustion chamber and damper generates forces which act on the control rod. The equation of motion of control rod is given by

$$\frac{dV_{rd}(t)}{dt} = \frac{P_c(t) (A_{pi} - A_{vr}(t)) - P_d(t) (A_d)}{m_{rd}} \quad (16)$$

$$\frac{dx_{rd}(t)}{dt} = V_{rd}(t) \quad (17)$$

The only force acting on the projectile is due to the pressure in the combustion chamber. The equations of motion are given by

$$\frac{dV_{pj}(t)}{dt} = \frac{P_c(t) A_{pj}}{m_{pj}} \quad (18)$$

$$\frac{dx_{pj}(t)}{dt} = V_{pj}(t)$$

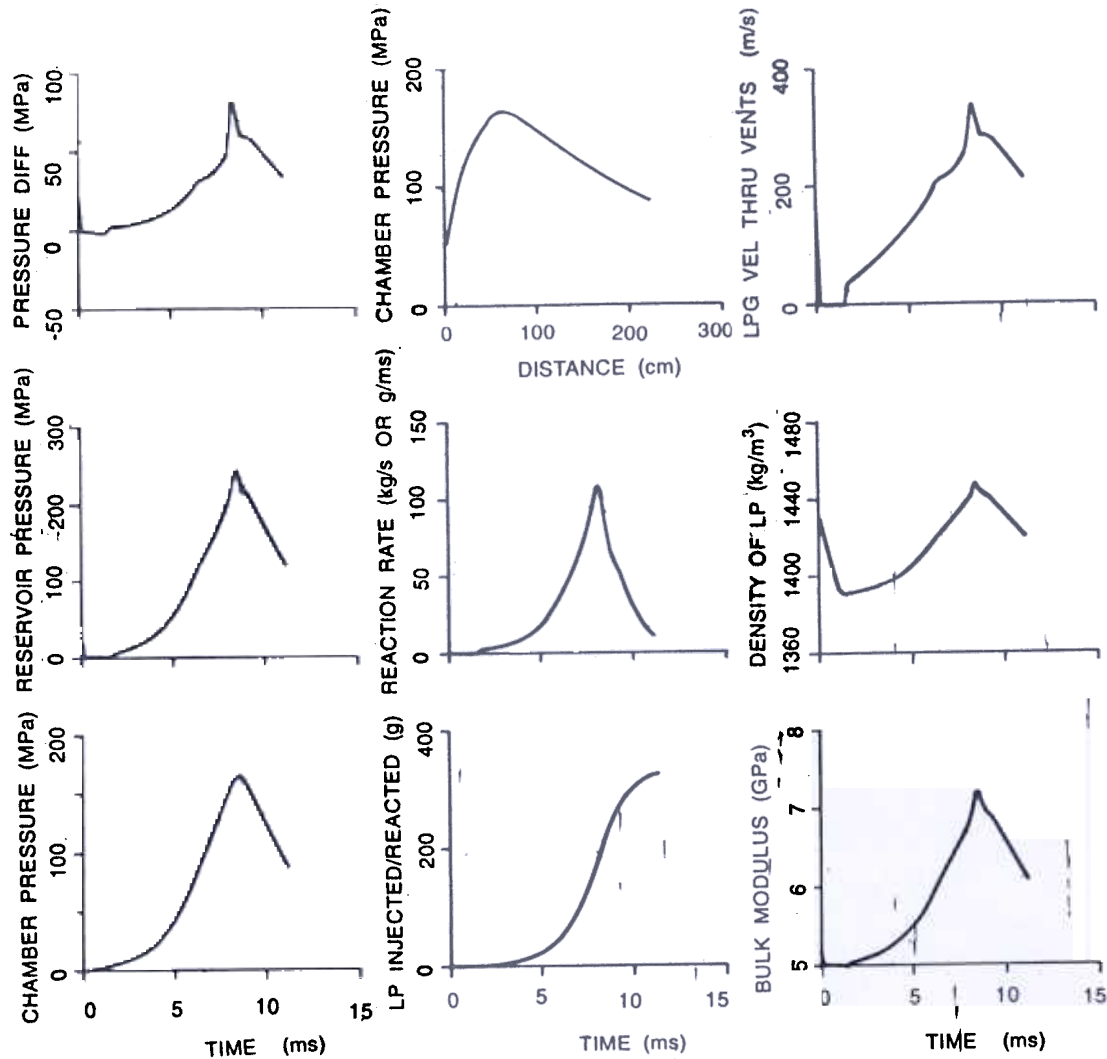


Figure 2. Time development of various interior ballistic parameters of 30 mm RLPG

The initial velocity and displacement of both the projectile and the piston are zero. The projectile is assumed to be stationary till a shot-start pressure is reached, which depends on the projectile design. These define the starting conditions for Eqns (14)-(19). The area of the vent depends on positions of the control rod and the annular piston and is given by

$$A_{vr}(t) = f(x_{pi}(t), x_{rd}(t)) \quad (20)$$

The pressure difference across piston head causes the liquid propellant to be injected into the chamber and the mass flow rate is given as

$$\frac{dM_{lp}(t)}{dt} = C_{vr} \rho_{lp}(t) A_{vr}(t) V_{vr}(t) \quad (21)$$

In cases where there is some leakage of lp from the gun due to seal failure, the mass of lp lost is given as

$$\frac{dM_{lp}(t)}{dt} = C_{lr} \rho_{lp}(t) A_{lr}(t) V_{vr}(t) \quad (22)$$

The damper fluid also ejects from the damper chamber to an auxiliary chamber and its mass is given by

$$\frac{dM_{df}(t)}{dt} = C_{vd} \rho_{df}(t) A_{vd}(t) V_{vd}(t) \quad (23)$$

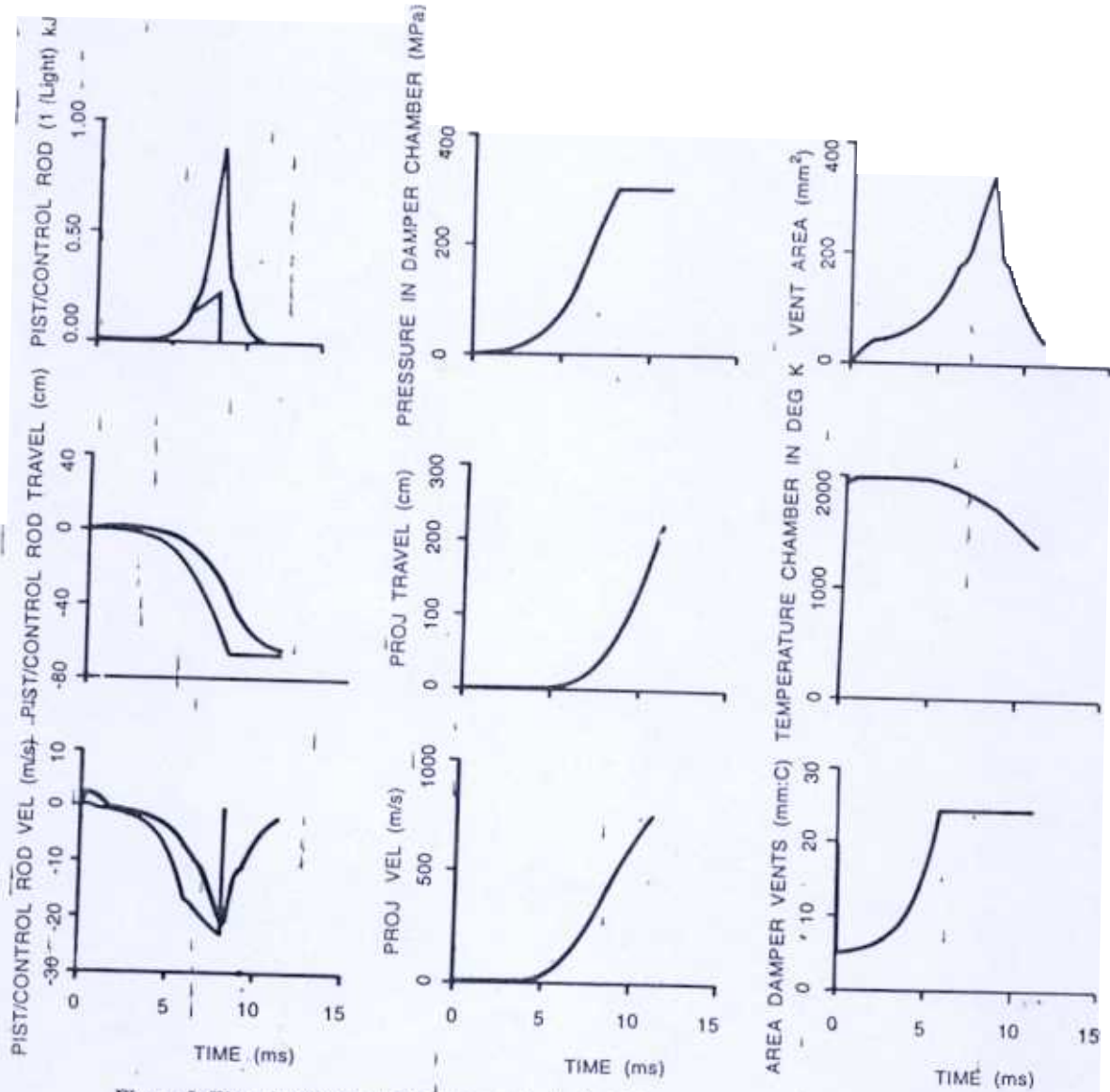


Figure 3. Time development of various interior ballistic parameters of 30 mm RLPG

The area of the damper is also a variable which depends on the control rod position and is given as

$$A_{vd}(t) = f[x_{rd}(t)] \quad (24)$$

If there is some leakage of df due to seal failure, then the mass of df lost is given as

$$\frac{dM_{ldf}(t)}{dt} = C_{ld} \rho_{df}(t) A_{ld}(t) V_{ld}(t) \quad (25)$$

The coefficient of discharge of the lp and df varies between 0 and 1 and is a user input. The

velocities of lp and df flowing through their respective vents are given by

$$V_{vr}(t) = \sqrt{\frac{[2(P_r(t) - P_c(t))]}{\rho_{lp}(t)}} \quad (26)$$

$$V_{vd}(t) = \sqrt{\frac{[2(P_d(t) - P_{atm})]}{\rho_{df}(t)}} \quad (27)$$

The velocity of the leakage of lp and df is given by

$$V_{lr}(t) = \sqrt{\frac{[2(P_r(t) - P_{atm})]}{\rho_{lp}(t)}}$$



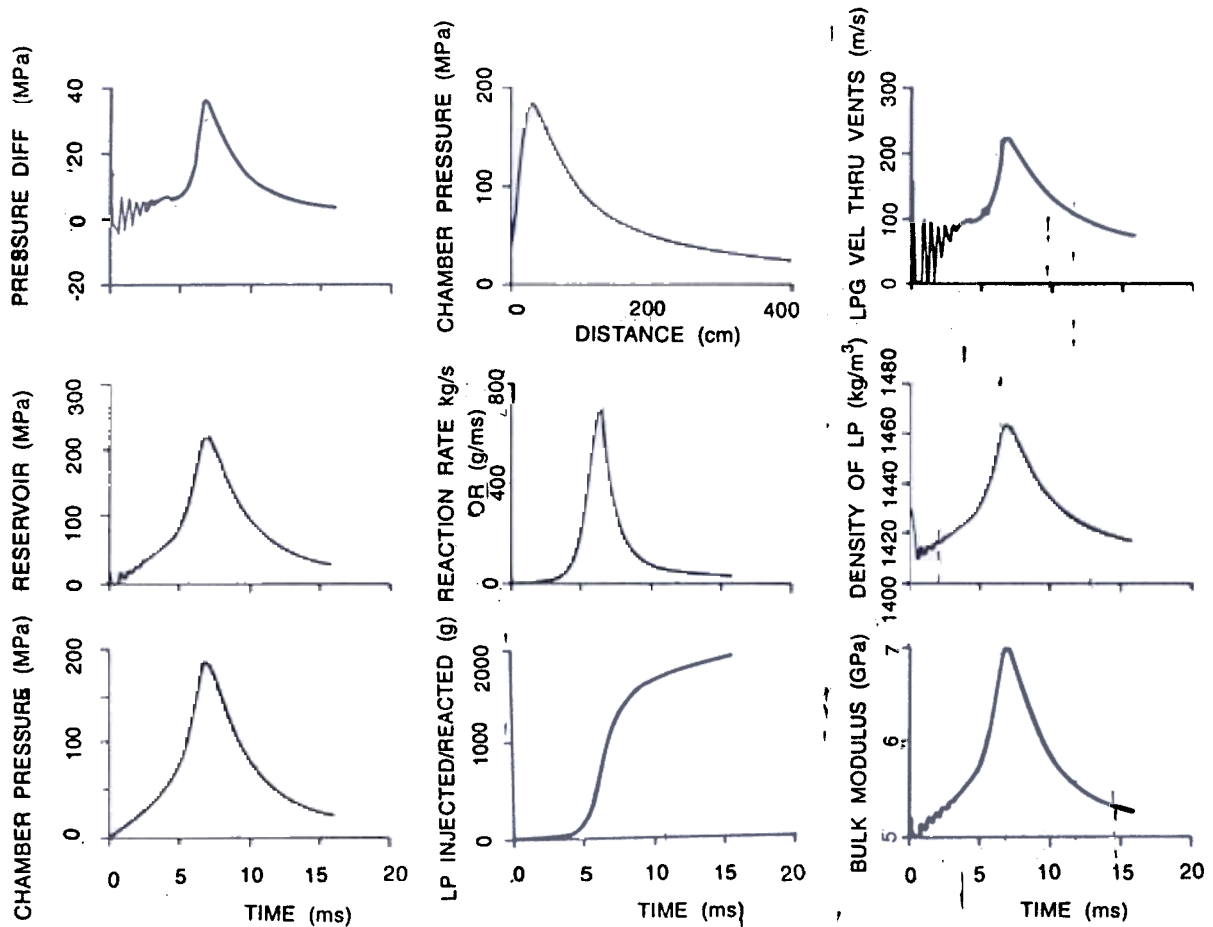


Figure 4. Time development of various interior ballistic parameters of 105 mm RLPG

$$V_{ld}(t) = \sqrt{\frac{2(P_d(t) - P_{atm})}{\rho_{df}(t)}} \quad (29)$$

The mass flow rate of the igniter lp is a user-defined constant and lasts till the entire igniter lp is exhausted.

$$Mr_{ip}(t) = r(\dot{A}) * t \quad (30)$$

The corresponding change in chamber volume is given by

$$\frac{dU_c(t)}{dt} = x_{pi}(t) A_{pi} + V_{pj}(t) A_{pj} \quad (31)$$

### 3. RESULTS AND DISCUSSION

Equations (1-31) are solved simultaneously on a computer, using modified Euler's method. The code was written in C-language. The software predicts the peak pressure in both chamber and reservoir, velocities of pistons and projectiles, injection rates of lp and df, etc., for different input

parameters. The input parameters used in the case of 30 mm and 105 mm guns are given in Table 1. The output parameters include the time development of chamber, reservoir and damper pressure and velocity and position of the projectile, annular piston and control rod. The program also gives the mass of lp injected, reacted and accumulated. Variation in injection, vent areas and the corresponding velocity and mass of df and lp ejected out through different vents are also included in the output. The time development graphs of these parameters are given in Figs 2 and 3 for 30 mm and in Figs 4 and 5 for 105 mm gun, respectively.

### 5. CONCLUSION

The program developed above is useful in designing an RLPG having an annular piston with

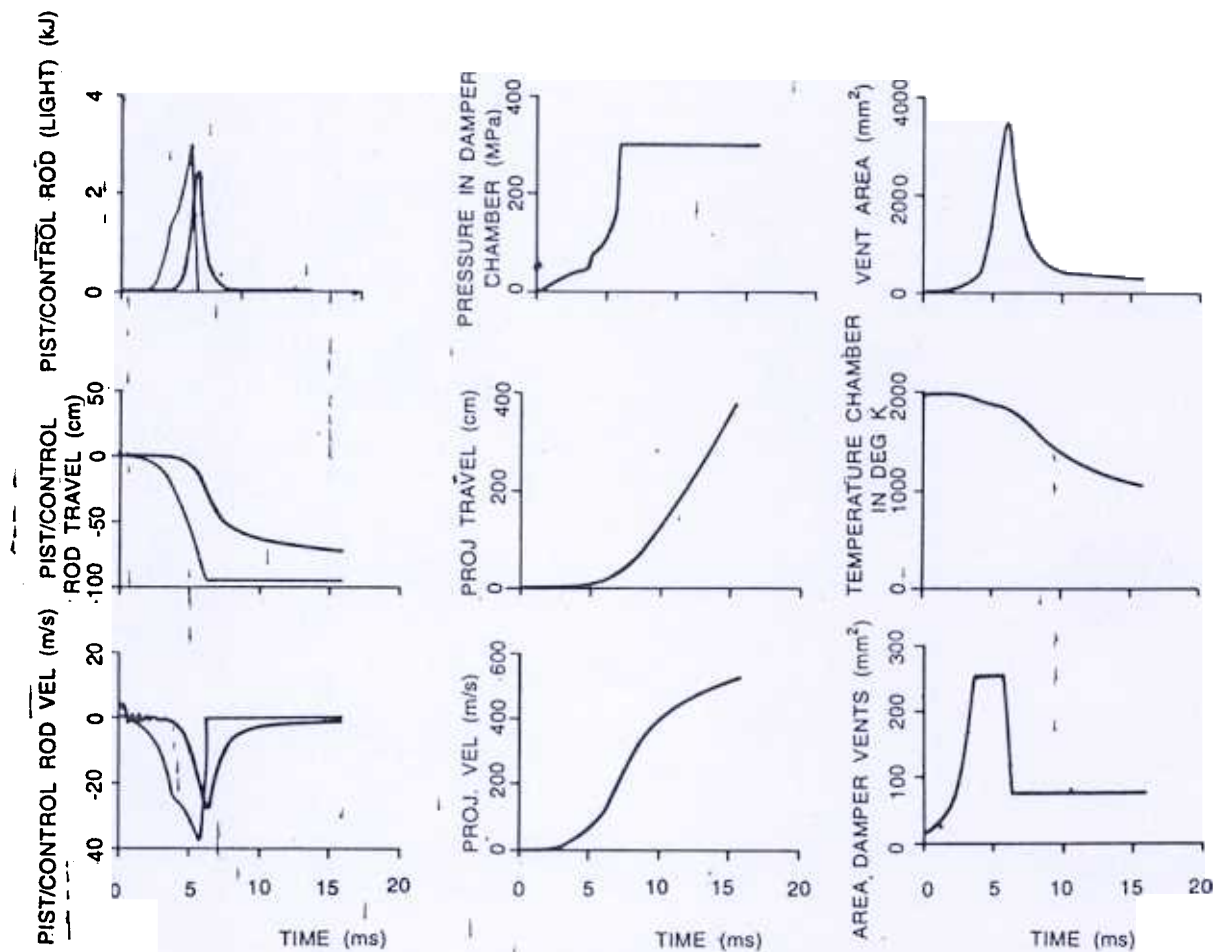


Figure 5. Time development of various interior ballistic parameters of 105 mm RLPG

a movable control rod. The program serves the general purpose and is also applicable to model either 30 mm, 105 mm or 155 mm guns. Unlike the inline piston where the injection vent area is constant, the annular piston gives a possibility of variable injection vent. It is possible to control the injection processes and thus the combustion by selecting suitable damper vent area. It could also be used for conducting sensitivity studies, which may be used as a basis for finalising the hardware design. Efforts towards the validation and improvement in the model are under study.

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Table 1. Input parameters of RLPG

| Input parameters                                      | 30 mm gun | 105 mm gun | Units           |
|---|-----------|------------|-----------------|
| Accumulation delay                                    | 0.00      | - 0.0      | $\mu\text{s}$   |
| Area of vents damper                                  | 24.335    | 253.0      | $\text{mm}^2$   |
| Bore of barrel  | 30.0      | 105.0      | mm              |
| Bore of chamber                                       | 85.0      | 177.0      | mm              |
| Bulk modulus of $df$                                  | 5000.0    | 5000.0     | MPa             |
| Bulk modulus of $lp$                                  | 5000.0    | 5000.0     | MPa             |
| Density of $df$                                       | 1.0       | 1.0        | g/cc            |
| Density of piston/rod material                        | 8000.00   | 8000.0     | $\text{kg/m}^3$ |
| Density of propellant                                 | 1.430     | 1.430      | g/cc            |
| Diameter (outer) of annular piston                    | 85.0      | 177.0      | mm              |
| Diameter of annulus of piston                         | 32.0      | 74.0       | mm              |
| Diameter of control rod damper portion                | 15.0      | 25.0       | mm              |
| Diameter of control rod reservoir portion             | 33.0      | 70.0       | mm              |
| Discharge coefficient vents $lp$                      | 0.850     | 0.850      |                 |
| Flame temperature of $lp$                             | 2200      | 2200       | K               |
| Fraction of energy lost in friction by annular piston | 0.1       | 0.1        |                 |
| Fraction of energy lost in friction by projectile     | 0.1       | 0.1        |                 |
| Fraction of energy lost in friction by control rod    | 0.1       | 0.1        |                 |
| Heat loss fraction in barrel                          | 0.100     | 0.1        |                 |
| Impetus of liquid propellant                          | 0.9       | 0.9        | kJ/g            |
| Impetus of igniter propellant                         | 0.900     | 0.9        | kJ/g            |
| Initial pressure in damper reservoir                  | 0.1       | 0.1        | MPa             |
| Inner diameter of annular piston                      | 75.0      | 167.0      | mm              |
| Larger diameter of control piston head                | 41.0      | 84.0       | mm              |
| Length of barrel                                      | 2.260     | 4.0        | m               |
| Length of control piston head                         | 24.0      | 45.0       | mm              |
| Length of damper chamber                              | 70.0      | 100.0      | mm              |
| Length of piston                                      | 200.0     | 210.0      | mm              |
| Length of reservoir chamber                           | 70.0      | 100.0      | mm              |
| Length of rod damper portion                          | 110.0     | 127.0      |                 |
| Length of rod reservoir portion                       | 100.0     | 120.0      | mm              |
| Mass of $df$  | 47.5      | 335.6      | g               |
| Mass of igniter propellant                            | 10.0      | 170.0      | g               |
| Mass of projectile                                    | 680.0     | 17000      | g               |
| Mass of propellant                                    | 356.4     | 2580.6     | g               |
| Pressure dependence factor beta                       | 9.0       | 9.0        |                 |
| Ratio of specific heat (gamma)                        | 1.3       | 1.3        |                 |
| Shot-start pressure of projectile                     | 25.0      | 25.0       | MPa             |
| Smaller diameter of control piston head               | 10.0      | 60.0       | mm              |
| Total igniter propellant energy                       | 27.3      | 463.6      | kJ              |
| Total mass of annular piston                          | 3.810     | 6.337      | kg              |
| Total mass of control rod                             | 0.839     | 4.191      | kg              |
| Volume of chamber                                     | 500.0     | 2000.0     | cc              |
| Volume of $df$  | 47.5      | 335.6      | cc              |
| Volume of $lp$ reservoir                              | 249.3     | 1804.0     | cc              |
| Ullage $df$   | 0         | 0          | %               |
| Ullage liquid propellant reservoir                    | 0         | 0          | %               |



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#### Contributors



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